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TRANSMITTAL FORM

(to be used for all correspondence after initial filing)

Application Number	10/588,981
Filing Date	August 10, 2006
First Named Inventor	Roderick Boswell
Art Unit	Unknown
Examiner Name	Unknown
Attorney Docket Number	F146
Total Number of Pages in This Submission	

ENCLOSURES *(Check all that apply)*

- [ ] Fee Transmittal Form
  - [ ] Fee Attached
- [ ] Amendment/Reply
  - [ ] After Final
  - [ ] Affidavits/declaration(s)
- [ ] Extension of Time Request
- [ ] Express Abandonment Request
- [ ] Information Disclosure Statement
- [x] Certified Copy of Priority Document(s)
- [ ] Reply to Missing Parts/ Incomplete Application
  - [ ] Reply to Missing Parts under 37 CFR 1.52 or 1.53
- [ ] Drawing(s)
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- [ ] Appeal Communication to TC **(Appeal Notice, Brief, Reply Brief)**
- [ ] Proprietary Information
- [ ] Status Letter
- [x] Other Enclosure(s) (please Identify below):

Remarks

Certified Copy is a true copy of the Provisional Specification in connection with Application No. 2003905709 for a patent by The Australian National University as filed on October 17, 2003.

SIGNATURE OF APPLICANT, ATTORNEY, OR AGENT

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The Australian National University

AUSTRALIA

Patents Act 1990

PROVISIONAL SPECIFICATION

for the invention entitled:

"Plasma Extraction Device"

The invention is described in the following statement:

PLASMA EXTRACTION DEVICE

This invention relates to the extraction of an ion beam from a plasma. The invention is particularly directed to the extraction of high brightness beams. Although there are several definitions of brightness, it is generally accepted that minimising emittance ensures the highest possible brightness for a given beam current. Emittance is a measure of the parallelism of the individual particle trajectories with-in a beam. In planar symmetry this means that particles follow rectilinear and parallel trajectories whilst in cylindrical and spherical symmetry they move along rectilinear paths that follow radial lines as though emmanating from or converging towards a single line or point. The present invention has application to diverging, converging and parallel ion beams extracted from rectangular slits and circular apertures. This corresponds to four basic beam types:

Strip Beams: parallel beams extracted through a slit

Wedge Beams: diverging/converging beams extracted through a slit

Cylindrical Beams: parallel beams extracted through a circular aperture

Conical Beams: diverging/converging beams extracted through a circular aperture.

There are a range of applications for ion beams particularly in the semiconductor industry. For example, the fabrication and correction of lithography masks involves a need for sub-micron etching capability. This processing is currently achieved using medium-energy particle beams

(10-50keV), most often ions, referred to as focused ion beams or FIBs. To ensure sub-micron feature creation, the FIBs must be focusable down to a nano-meter scale spot. This requires the extraction of very high brightness beams in excess of $10^5 A.sr^{-1}.m^{-2}$. Liquid metal ion source (LMIS) technology has been capable of this level of brightness for several decades. It exploits the capillary effect of liquid Gallium to cover a sharp Tungsten needle onto which a strong electric field is applied and consequently ions are removed by field effect. The field effect is strongest at the needle point and so a beam of ions is created that appears to emanate from a nanometer spot. This beam is then accelerated and focused onto the target where it etches the surface by surface collision processes.

Though this technology boasts a nanometer scale milling capability, it produces nefaterious doping effects by introducing Gallium into Silicon. To avoid this a high brightness beam of inert gas ions would be preferable. This could be achieved by extracting ions from an inert gas plasma. However, this has proven notoriously difficult and has been the subject of intense study for some decades. Much work has been done to optimise extraction electrodes in a number of ways. For example adjustment of aperture ratios and electrode spacings is described in J.R. Coupland, T.S. Green, D.P. Hammond, and A.C. Riviere, *A study of the ion beam intensity and divergence obtained from a single aperture three electrode extraction system,* Rev. Sci. Instrum., 44(9):1258, 1973. Shaping of electrodes has also been investigated as described in D.E. Radley, *The theory of the pierce type electron gun*, J. Electron. Control, 4:125, 1957, E.R. Harrison, *Approximate electrode shapes for a*

cylindrical electron beam, Brit. J. Appl. Phys., 5:40, 1953 and P.N. Daykin, *Electrode shapes for a cylindrical electron beam*, Brit. J. Appl. Phys., 6:248, 1955.

Despite these efforts brightness in excess of $10^5 A.sr^{-1}.m^{-2}$ has not been achieved.

Accordingly this invention provides for a plasma extraction device for extraction of a high brightness ion beam of selected profile said device including at least three sequentially arranged electrodes each respectively having an aperture corresponding to the selected beam profile, a first of said electrodes adjacent said source being maintained at an extraction potential, a second of said electrodes being spaced from the first electrode and maintained at a first blocking potential opposite to said extraction potential; and a third of said electrodes disposed between said first electrode and said second electrode and maintained at a selected potential between said extraction potential and said first blocking potential; said first, second and third electrodes being shaped to produce substantially zero electric field at said third electrode.

Preferably, the extraction device includes a further two sequentially arranged fourth and fifth electrodes each respectively having an aperture corresponding to the selected beam profile and disposed on the side of said second electrode remote from the plasma, said fourth electrode being between said second and fifth electrodes and maintained at a second blocking potential less than said first blocking potential and said fifth electrode being maintained substantially at zero potential, the fourth and fifth electrodes being shaped to maintain substantially zero

electric field at the second and fifth electrodes.

In preferred forms of the invention the beam profile is one of a strip beam, a wedge beam, a cylindrical beam, and a conical beam.

These beams can be thought of as sections of current flowing in complete diodes. Consequently, parallel beams can be treated in the same way as a planar diode, divergent/convergent beams extracted through a rectangular slit can be treated as a cylindrical diode and divergent/convergent beams extracted through a circular aperture can be treated as a spherical diode. In each case, the plasma/beam interface or plasma meniscus is the anode (emitter) and the 0V equipotential surface is the cathode (collector). The purpose of the extraction device is to ensure that the meniscus and 0V equipotential surfaces are parallel in the case of parallel beams and concentric cylinders or spheres in the case of diverging or converging beams. If this situation is maintained then, neglecting the inherent ion temperature in the plasma, the ions travel in perfect parallelism along radial lines from the meniscus to the 0V equipotential and suffer no deflection. In other words the beams have zero emittance growth.

In accelerating the beam, however, a significant electric field can be produced in the direction of flow. In accordance with the present invention this is compensated to avoid the electric field in the beam from ballooning outwards at the exit of the extractor and deflecting the ion trajectories.

In the transport region aft of the extractor, considerable

advantage can be gained by the presence of electrons which neutralise the beam space charge. However, their presence in the extractor, especially in the acceleration gap, is highly detrimental to beam quality since they alter the charge density distribution and hence the potential structure through-out the extractor. The existence of an electric field at the exit to the extractor would serve to accelerate electrons into the extraction region in such quantity as to neutralise the electric field at the extractor exit. Accordingly the present invention ensures that the beam potential has zero electric field upon exit of the extractor.

The electrons in the beam plasma aft of the extractor have non-zero temperature and are generally distributed according to Maxwell's law. This means that higher energy electrons from the tail of the distribution are able to enter the extractor if a blocking field is not present. To this end a small blocking potential preferably of some hundred Volts is produced at the end of the extraction region to inhibit the passage of electrons. Again, to avoid ballooning of the electric field this potential must be produced so that the electric field upon exit of the blocking region is zero.

In a preferred form of the invention the potential distribution in the beam will then have the form shown in Figure 1. There are two regions called the Extraction and Blocking regions both of which are divided into two stages. Stage 1 serves to take the beam from a low gradient to a high gradient and stage 2 vice versa. In the Extraction gap, stage 1 is necessary to match the beam potential to the plasma sheath and stage 2 to bring the electric field to

zero. A similar rationale is behind the two stages of the blocking region.

The extractor region is formed by the first three sequential electrodes. Stage 1 and stage 2 are separated by the third electrode. The first electrode is preferably the plasma electrode. The second electrode and third electrode are usually referred to as the blocking and accelerating (Accel) electrode respectively.

The blocking region is formed between the second electrode and the fifth electrode. Stage 1 and stage 2 are separated by the fourth electrode.

In order to describe the plasma extractor device of the present invention it is firstly necessary to provide some analysis of beam distributions and an overview of solutions to Laplaces equation for different beam profiles. This will be done in separately headed sections which proceed an explanation of electrode design and specific examples of the invention. Reference will be made to the accompanying drawings in which:

Figure 1 is a schematic graph of potential distribution in a beam extracted according to the present invention;

Figure 2 is a schematic representation of a diverging beam showing the extractor and blocking stages according to the present invention;

Figure 3 is a graph of generalised distribution versus Langmuir-Blodgett;

Figure 4 illustrates a contour C used in equation (46);

Figure 5 is a plot of electrode geometries forming a plasma extraction device according to the invention for a 5°

diverging wedge beam; and

Figure 6 is an enlargement of part of the plot of Figure 5.

Figure 1 shows the general shape of the potential along the beam inside the extractor for low emittance growth extraction (zero emittance growth in the ideal case). The details of these distributions in each stage of the extractor are first explained.

The overall potential profile shown in Figure 1 is in fact four distributions concatenated. Each stage is bounded by two plane or two concentric surfaces depending on the beam type, so that each stage can be treated as separate, 'complete' diodes, each with its own set of boundary conditions. To get the complete distribution, the solutions are stitched together by matching the boundary conditions at each surface.

The potential and charge distributions in the beam at each stage of extraction are governed by Poisson's law. The basic solution to this problem, using simple boundary conditions, in plane symmetry was solved by Child and Langmuir in 1911 and 1914 respectively and in cylindrical and spherical symmetry by Langmuir and Blodgett in the 1920s. These initial solutions assumed only one charged particle species (notably electrons), and ignored initial velocity.

In accordance with the present invention several generalisations are introduced. In particular, distributions describing non-zero initial gradient, distributions describing non-negligible initial velocity, distributions tapering from a strong gradient to a zero gradient (the reverse of the standard Langmuir-Blodgett

solution) and distributions describing the presence of Maxwellian electrons. A further requirement on these distributions is that they have the same form as the standard Langmuir-Blodgett series solutions since the Radley solutions to Laplace's equation are dependent on this form.

The work published by Langmuir-Blodgett in the 1920s forms the basis for the beam distribution analysis that follows and is given in terms of simple and compact series solutions. A cursory mathematical overview of Langmuir-Blodgett's contribution starting with spherical symmetry and working through cylindrical to planar symmetry is provided.

In the case of ion beam extraction from a circular aperture, the charge and potential distributions in the beam are assumed to be analogous to those in a complete spherical diode. Following Langmuir and Blodgett, Poissons' equation between two concentric spheres can be stated as

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dV}{dr}\right)=\frac{\rho}{\varepsilon_0} \qquad (1)$$

where V is the potential at a point distant r from the common center and ρ is the ion charge density. The current flowing in the diode can be written in terms of the particle velocity v:

$$I=4\pi r^2 \rho v \qquad (2)$$

where the velocity can be written in terms of the voltage V by using the kinetic energy relation:

$$\frac{1}{2}Mv^2=-eV \qquad (3)$$

Combining equations (1), (2) and (3) yields:

$$r^2 \frac{d^2V}{dr^2} + 2r\frac{dV}{dr} = A \cdot \tilde{V}^{-\frac{1}{2}} \qquad (4)$$

where $\tilde{V} = -V$, and:

$$A = \frac{I}{4\pi\varepsilon_0}\sqrt{\frac{M}{2e}} \qquad (5)$$

Equation (4) can probably not be integrated directly but a solution can be found in terms of a series. The form of the solution as a function of the ratio $R=r/r_s$

$$V(R) = \left(\frac{9}{4}A\right)^{\frac{2}{3}} f^{\frac{4}{3}}(R) \qquad (6)$$

where f is the analytic function to be found. The $\left(\frac{9}{4}A\right)^{\frac{2}{3}}$ term serves to normalise for the constant term A related to the current and hence the plasma density and meniscus curvature, and the $f^{\frac{4}{3}}(R)$ term to remove the square root from ($) and hence to simplify subsequent derivations. One further transformation is performed by setting:

$$\gamma = \ln(R) \qquad (7)$$

so that a solution to (6) can be expressed in terms of a MacLauren series:

$$f = \sum_{n=0}^{\infty} a_n y^n \qquad (8)$$

substituting (6) into (4) and imposing equation (7) results in:

$$3ff' + f'^2 + 3ff'' - 1 = 0 \qquad (9)$$

where $f' = df/d\gamma$ and $f'' = d^2f/d\gamma^2$. From this form it can be

seen that for $f=0$, $f'=1$. The first six terms of the series solution are then:

$$f=\gamma-0.3\gamma^2+0.075\gamma^3-0.0143182\gamma^4+0.0021609\gamma^5-0.00026791\gamma^6 \quad (10)$$

where this corresponds to the case $V=0$ and $V'=0$.

A similar derivation can be made for the case of cylindrical symmetry. Poisson's equation becomes:

$$r\frac{d^2V}{dr^2}+\frac{dV}{dr}=B\cdot\tilde{V}^{\frac{1}{2}} \qquad (11)$$

where:

$$B=\frac{I}{2\pi rl\sqrt{\frac{m}{2e}}} \qquad (12)$$

and l is the length of the extraction slit. The solution takes the form:

$$V=\left(\frac{9}{2}Br\right)^{\frac{2}{3}}g^{\frac{4}{3}} \qquad (13)$$

where g is the analytic function to be found over the desired range of r. Again substituting (13) into (11) and setting (7), results in:

$$3gg''+g'^2+4gg'+g^2-1=0 \qquad (14)$$

Again, for $g=0$, $g'=1$ and the series becomes:

$$g=\gamma-0.4\gamma^2+0.0916667\gamma^3-0.01424242\gamma^4+0.001679275\gamma^5-0.0001612219\gamma^6 \quad (15)$$

That this corresponds to the case $V=0$ and $V'=0$.

2.2 Non-Zero Initial Gradient

The present invention is direct to the extraction of ions from plasma, the assumption that the electric field at the meniscus surface is zero, central to the Child-Langmuir and Langmuir-Blodgett derivations, is incorrect and so will be generalised. Furthermore, the final result will be presented in a similar, easy to use series formulation as the original Langmuir-Blodgett relation.

Figure 3 demonstrates the effect of non-zero initial gradient. The dashed line corresponds to the case of a divergent conical beam extracted from a plasma of density $n = 10^{14} cm^{-3}$ and is compared to the standard Langmuir-Blodgett distribution which assumes zero initial gradient.

To understand why the gradient at the plasma/sheath interface is meniscus is non-zero it is necessary to consider the Bohm sheath criterion which stipulates the minimum ion velocity for entry into the sheath to maintain a stable sheath at a plasma boundary. In conjunction with some distribution relation for electrons, this defines a potential structure with-in the sheath. In particular, the electric field at the plasma boundary is non-zero and is typically several hundred kilo-Volts per meter. For continuity of the electric field across the plasma/beam interface the potential gradient must be equal on both sides of this surface. This is not assured by the original assumptions of Langmuir and Blodgett who were modelling particle flow from thermionic cathodes. In that case the source of particles was assumed to be undeletable and to have no intrinsic electric field so that for equilibrium the boundary condition in the extractor was for the electric

field to be zero at the entry to the acceleration gap. In the case of plasmas, the flux of ions is fixed and an intrinsic electric field does exist in the sheath which separates the beam from the bulk plasma. This strongly implies that particle beam extraction from plasmas is not space charge limited but rather is source limited and further that the voltage distribution in the beam is not given by the Langmuir-Blodgett relation as it is usually stated.

General solutions to Poisson's equation for the case of non-zero initial gradient are first present followed by a discussion of the plasma sheath and how the gradient at the meniscus is obtained.

Spherical Symmetry

Taking the first derivative of (6), yields:

$$V'(\gamma) = \lambda\sqrt{p} \qquad (16)$$

where $\lambda = \frac{4}{3}\left(\frac{9}{4}A\right)^{\frac{2}{3}}$ and $p = f'(\gamma)^2 f(\gamma)^{\frac{2}{3}}$, for $\gamma = 0$. In the classic Langmuir-Blodgett derivation $f(\gamma) = 0$ in (9) leads to $f'(\gamma) = 0$, for $\gamma = 1$, (assuming potential increases as a function of position in the extractor), so that $p = 0$ and hence $V'(\gamma = 0) = 0$. In other words, the Langmuir-Blodgett derivation requires a zero initial gradient in potential. Numerically, however, it is possible to have f approach zero without requiring $V'(0)$ to annul by setting $f'(0)$ such that (16) holds for the desired value of $V'(0)$. For a given value of $V'(0)$ and A, there is a limit to how small $f(0)$ can be set, but in

most practical cases it is several orders of magnitude less than unity.

The solution depends only on p, rather than the individual values of $f(0)$ and $f'(0)$, for the range of p which is of interest. The series coefficients, a_n, are expressed as a quadratic:

$$a_n = \alpha_n + \beta_n p + \gamma_n p^2 \qquad (17)$$

where α_n, β_n and γ_n are the expansion coefficients found by a least squares method. These terms are presented in the following table 1.

n	α_n	β_n	γ_n
1	1.0035	4.049	-10.92
2	-0.3084	-8.008	25.11
3	0.08338	7.791	-25.85
4	-0.01825	-3.96	13.47
5	0.002870	1.0004	-3.448
6	-0.0002227	-0.09904	0.3441

Table 1: Expansion terms for the coefficients of the MacLauren series (see equation 17). Spherical case. Note: the α_n are very close to the original Langmuir-Blodgett series coefficients.

Cylindrical Symmetry

Taking the first derivative of the potential and writing it in terms of the parameter p :

$$V'(R) = \mu\left(g^{\frac{4}{3}} + 2\sqrt{p}\right) \qquad (18)$$

where $\mu = \frac{2}{3}\left(\frac{9}{2}Be^{\gamma}\right)^{\frac{2}{3}}$ and $R = 1$, and note that in the limit the term in g disappears, so that $V'(R) \approx 2\mu\sqrt{p}$. This has the same form as the spherical case, so that by writing:

$$g = \sum_{n=0}^{\infty} b_n \gamma^n \qquad (19)$$

and plotting the series coefficients in terms of the parameter p yields:

$$b_n = \delta_n + \varepsilon_n p + \zeta_n p^2 \qquad (20)$$

where δ_n, ε_n and ζ_n are coefficients found in the same fashion as for the spherical case. Results are presented in table 2.

n	γ_n	δ_n	ε_n
1	1.0034	3.989	-10.69
2	-0.4086	-8.223	25.43
3	0.1005	7.974	-26.22
4	-0.01866	-4.038	13.65
5	0.002658	1.0184	-3.491
6	-0.0002011	-0.1007	0.3482

Table 2: Expansion terms for the coefficients of the MacLauren series (see equation 20). Cylindrical case. Note: the γ_n are very close to the original Langmuir-Blodgett series coefficients.

Planar Symmetry

The Plasma Sheath

There are several ways to model the sheath. A method in terms of the Bohm sheath criterion and the Boltzman equation in one dimension, which is easily extended to spherical and cylindrical symmetry is described in full in M. A. Liberman and A. J. Lichtenberg "*Principles of Plasma Discharges and Materials Processing*" John Wiley & Sons, New York, 1st edition, 1994. This model incorporates both the non-zero ion velocity v_B at the entry to the sheath, required by the Bohm criterion, and also the presence of electrons. Another popular method is the Child sheath, which is extended to spherical and cylindrical symmetry by the use of the standard Langmuir-Blodgett corrections. In this case, the pre-sheath/sheath boundary and the meniscus are considered to be concentric spheres for extraction from a circular aperture and concentric cylinders for extraction from a slit. Though solving the Boltzman sheath is possible in terms of a series, it requires a somewhat more drawn out analysis and so for simplicity, the Child sheath method will be employed with Langmuir-Blodgett corrections. As such, the pre-sheath can be ignored and we assume that the velocity of ions and the potential at the bulk plasma/sheath edge are zero. However, it should be noted that the Child sheath yields smaller gradients than the Boltzman sheath.

Sheath Potential at the Meniscus

To solve (4), the case of extraction fro a plasma requires I must equal the ambipolar flux for ions:

$$I^{+} = 0.6 \cdot e \cdot n_s \cdot v_B \cdot \mathrm{A} \qquad (21)$$

where n_s is the plasma density at the sheath edge and $A = 4\pi r_s^2$ is the area over which current is extracted, r_s being the radius of curvature of the sheath. It follows from (5) and (21), that the solution to (4) is strongly relates to both n_s and r_s.

In addition, three boundary conditions are required. At the entry to the sheath set $V(1) = 0$ and $\frac{dV(1)}{dR} = 0$. To determine the sheath potential at the meniscus equate ion flux, assumed constant through-out the sheath

$$\Gamma_i = \frac{n_s v_B}{R^2} \qquad (22)$$

to the electron flux at the meniscus,

$$\Gamma_e \frac{n_s(\bar{v}_e)e^{\frac{eV_m}{kT_e}}}{4R^2} \qquad (23)$$

where $\bar{v}_e = (8eT_e/\pi m)^{\frac{1}{2}}$ is the mean electron velocity and V_m is the potential of the meniscus with respect to the plasma-sheath edge. Thus upon substitution of the Bohm velocity:

$$n_s\left(\frac{eT_e}{M}\right)^{\frac{1}{2}} = \frac{1}{4}n_s\left(\frac{8eT_e}{\pi m}\right)^{\frac{1}{2}} e^{\frac{eV_m}{kT_e}} \qquad (24)$$

which becomes:

$$V_m = -T_e \ln\left(\frac{M}{2\pi m}\right)^{\frac{1}{2}} \qquad (25)$$

This can be expressed in a more convenient form by substituting the mass of the extracted ion species. Krypton is a typical gas used in ion beam extraction from plasmas and has a mass of $M = 84au$. Therefore in this case, (25) can

be rewritten as $V_m = -5.05T_e$, which, assuming $T_e = 3eV$, is approximately -15V. This now leads to suitable boundary conditions for (4):

$$\begin{cases} V = 0V & ,r = r_s \\ V = -15V & ,r = r_m \\ dV/dR = 0 & ,r = r_s \end{cases} \qquad (26)$$

where r_m is the radius of curvature of the meniscus.

Potential Gradient at the Meniscus

Since both the voltage and its first derivative are zero at r_s, f is independent of the parameter p, from the familiar Langmuir-Blodgett relation:

$$\alpha(\gamma) = \gamma - 0.3\gamma^2 + 0.075\gamma^3 - 0.0143182\gamma^4 + 0.0021609\gamma^5 - 0.00026791\gamma^6 \quad (27)$$

This series expansion in conjunction with (6) and the boundary conditions now determine both the sheath width and the potential gradient at the meniscus edge. The sheath width is taken as the value of r_m-r_s for which (6) is equal to (25). The potential gradient at the meniscus edge is then equal to the first derivative of (6) taken at this value of r_m.

Assuming a constant electron temperature and gas type, equations (6), (7) and (27) show that the potential gradient at the meniscus edge is dependent on the bulk plasma density and the radius of curvature of the meniscus.

Solving Poisson's Law Backwards

To solve this consider the standard Langmuir-Blodgett problem in reverse, solving the differential equations from the exit of the extractor where the gradient is zero to the entry where it is large. This is tantamount to reversing the distribution in the case of a parallel beam or solving for the opposite convergence in the case of divergent or convergent beams.

The f and g series as defined by 10 and 19 remain unchanged however the definition of R and hence γ is altered. In the case of a diverging beam, R is taken to be the ratio of the current position to the first concentric surface and thus greater than unity. But in the case where Poisson's equation is solved backwards it is redefined to be the ratio of the current position to the second concentric surface and hence less than one. The inverse is true for a convergent beam.

Presence of Electrons

To account for the presence of a population of electrons arriving from the tail of a Maxwellian distribution an exponential term is added to the original differential equations to account for the Boltzman relation.

Generalising for the presence of electrons involves only the RHS of Poisson's law:

$$\frac{\rho}{\varepsilon_0} = \frac{e(n_i - n_e)}{\varepsilon_0} \qquad (28)$$

Since the electrons belong to a Maxwellian distribution their density as a function of potential is given by Boltzman's law:

$$n_e = n_0 \exp\left(\frac{eV}{kT_e}\right) \qquad (29)$$

where n_0 is some percentage ζ of the ion density in the beam aft of the extractor to take into account the fact that neutralisation is not always 100%. The differential equations for spherical, cylindrical and planar symmetry then become:

$$r^2V'' + 2rV' = 0.6ne\left[\frac{\widetilde{A}}{\sqrt{V}} + \zeta\exp(C)\right], \quad where \quad \widetilde{A} = v_B A\sqrt{\frac{M}{2e}}$$

(30)

$$rV'' + V' = 0.6ne\left[\frac{\widetilde{B}}{\sqrt{V}} + \zeta\exp(C)\right], \quad where \quad \widetilde{B} = v_B\sqrt{\frac{M}{2e}}$$

when n is the ion density in the beam, A is the area of the anode and $C = \frac{eV}{kT_e}$. Here the solutions take a very different form to those presented previously on account of the exponential term. However, it is possible to give a solution of the potential in terms of a MacLauren series, which when suitably normalised yields the correct form for implementation in the solutions to Laplace's equation.

Non-Zero Initial Velocity

The problem is set out in the same fashion as in section 2.1 for negligible initial velocity, except that now the kinetic energy relation is written:

$$\frac{1}{2}Mv^2 - \frac{1}{2}Mv_0^2 = eV \qquad (31)$$

This when rearranged yields:

$$v=\sqrt{\frac{2e}{M}V+v_0^2} \qquad (32)$$

But since:

$$v_0^2=\sqrt{\frac{2e}{M}V_{ext}} \qquad (33)$$

where V_{ext} is the energy of the particles at the exit of the previous stage, the differential equations stipulated by Poisson's law become for spherical, cylindrical and planar symmetries:

$$\begin{aligned} r^2V''+2rV' &= \frac{A}{\sqrt{V+V_{ext}}} \\ rV''+V' &= \frac{B}{\sqrt{V+V_{ext}}} \end{aligned} \qquad (34)$$

And the solutions to these equations become:

$$\begin{aligned} V &= \left(\frac{9}{4}A\right)^{\frac{2}{3}} f^{\frac{4}{3}} - V_{ext} \\ V &= \left(\frac{9}{2}Br\right)^{\frac{2}{3}} g^{\frac{4}{3}} - V_{ext} \end{aligned} \qquad (35)$$

Importantly, upon substituting (35) into (34), (9) and (14) remain unchanged. This means that the initial velocity serves only to translate the solution vertically. The *f* and *g* series can still be obtained by the various means set out previously.

Laplace's Equation

In a given region of the extractor according to this invention, determining the electrode geometry amounts to solving Laplace's equation subject to the potential along the beam edge. Since in the three cases of interest, plane, cylindrical and spherical geometry there is strong symmetry, this means that compact solutions can be obtained. These were presented by Radley [3] in 1957 along with a complete and rigorous mathematical derivation. A cursory overview is provided in the following.

However, before doing so it is noted that in treating the instability issues of the solution, Radley remarks that in as much as small variations of the initial surface can produce large differences in the solution so, conversely, do relatively large variations in electrode shapes away from the beam surface produce only small variations in the form of the beam surface. This will have important implications in the section *Electrode Design* because electrodes will have to be curtailed to avoid overlap or break-down proximity.

Strip Beam

A strip beam can be thought of as an infinite plane diode in which the cathode is the plane $x=0$ and all charge in the region $y>0$ has been suppressed. To determine electrodes that would extract a beam of this sort a family of equipotentials in $y>0$ must be found such that the conditions in $y<0$ are unchanged. The basic case of the potential distribution in space-charge limited flow when suitably normalised yields:

$$V = x^{\frac{4}{3}},\ \ in\ y \le 0 \qquad (36)$$

Since, assuming zero ion temperature, the trajectories are rectilinear and perpendicular to the emission surface defined by the extraction slit, the transverse forces on the beam at the beam edge are zero, so that $\delta V / \delta y = 0$ there. Restating the conditions in polar coordinates, gives:

$$\left.\begin{array}{l} V = r^{\frac{4}{3}} \\ \dfrac{\delta V}{\delta \theta} = 0 \end{array}\right\} \text{ on } \theta = 0 \qquad (37)$$

The solution in Cartesian coordinates is:

$$V(x, y) = \mathrm{Re}\left\{ z^{\frac{4}{3}} \right\} \qquad (38)$$

where

$$z = x + iy = r \cdot e^{i\theta} \qquad (39)$$

so that the solution is given by the conformal mapping:

$$W = V + iU = z^{\frac{4}{3}} \qquad (40)$$

Wedge Beam

For a wedge beam it is assumed that the meniscus and 0V equipotential surfaces are concentric cylinders. The coordinate system is therefore chosen so that the origin is at the vertex of the wedge, and the beam surface lies on $\theta=0$. Since the trajectories are rectilinear, lying along the lines θ=const., $\delta V / \delta \theta = 0$ on $\theta=0$. The meniscus is taken to be $r=r_m$ and the cathode to lie somewhere in the region

$r>r_m$ in the case of divergent beams and $r<r_m$ in the case of convergent beams. In the following it is assumed that the ratio $R=\frac{r}{r_m}$ is greater than unity or that the wedge is divergent. The potential distribution along the beam edge, when suitably normalised, is given by:

$$V=R^{\frac{2}{3}}\beta^{\frac{4}{3}} \qquad (41)$$

where β is an infinite power series in the variable $\gamma=\ln(R)$. (41) can be rewritten in series form:

$$V=R^{\frac{2}{3}}\left[\sum_{n=1}^{\infty}a_n\gamma^n\right]^{\frac{4}{3}} \qquad (42)$$

Since $a_1=1$, this last expression may be expanded by the multinomial theorem, to give:

$$V=R^{\frac{2}{3}}\gamma^{\frac{4}{3}}\sum_{n=1}^{\infty}b_n\gamma^{n-1} \qquad (43)$$

The coefficients b_n will be presented and discussed later. The potential outside the beam is obtained by writing $R\cdot e^{i\theta}$ for R in (41). Thus γ is replaced by $\omega=\gamma+i\theta$, so that:

$$V=\mathrm{Re}\left[R^{\frac{2}{3}}\cdot e^{\frac{2}{3}i\theta}\omega^{\frac{4}{3}}\sum_{n=1}^{\infty}b_n\omega^{n-1}\right] \qquad (44)$$

Cylindrical Beam

For this case cylindrical polar coordinates (r,θ,z), are enlarged with the axis of the beam along $r=0$. By suitably normalising the coordinates, the beam surface can be taken as $r=1$. Since the system has axial symmetry, none of the

variables involves θ, so this coordinate may be neglected. The ion flow considered is a cylindrical section of an infinite plane diode so that:

$$\left.\begin{array}{l} V = z^{\frac{4}{3}} \\ \dfrac{\delta V}{\delta r} = 0 \end{array}\right\} \text{ on } r=1 \qquad (45)$$

Applying the analysis in Radley, the solution is:

$$V(r,z) = \frac{1}{2}\pi \frac{1}{\left(-\frac{7}{3}\right)!\left(\exp\left(-\frac{14i\pi}{3}\right)-1\right)} \int_C \frac{\exp(-pz)}{p^{\frac{4}{3}}} \left(J_1(p)Y_0(pr) - Y_1(p)J_0(pr)\right)dp \qquad (46)$$

where p is a complex parameter, J and Y are Bessel functions of the first and second kind and C is the contour defined as shown in Figure 4.

In reality, the contribution of both straight line segments in C cancel and the contour reduces to a circle of radius ρ. In theory any value of ρ will work but it has been found that values of between 1 and 5 produced the most rapid and accurate results.

Conical Beam

Spherical polar coordinates (r, θ, ϕ), are employed with a cone semi-angle of $\theta = \theta_0$, the anode on the sphere $R=1$ and the cathode in the region $R>1$ in the case of a diverging beam and $R<1$ in the case of a converging beam. Again a diverging beam for this is assumed derivation. Writing $\gamma = \ln(R)$ and suitably normalising the potential gives:

$$V = f^{\frac{4}{3}} \qquad (47)$$

where

$$f = \sum_{n=1}^{\infty} = c_n \gamma^n \qquad (48)$$

The coefficients c_n depend on the boundary conditions for the beam and are discussed elsewhere. Again this series representation is expanded using the multinomial theorem and becomes:

$$V = \gamma^{\frac{4}{3}} \sum_{n=1}^{\infty} d_n \gamma^{n-1} \qquad (49)$$

The boundary conditions to be applied are:

$$\left.\begin{aligned} V &= f^{\frac{4}{3}} \\ \frac{\delta V}{\delta r} &= 0 \end{aligned}\right\} \text{ on } \theta = \theta_0 \qquad (50)$$

and following Radley gives:

$$V(r,\theta) = \sum_{n=1}^{\infty} \frac{d_n \sin^2(\theta_0)}{\left(\exp\left(-\frac{14 i\pi}{3}\right)-1\right)\left(-n-\frac{4}{3}\right)!} \int_C \frac{\exp(-\upsilon\gamma)}{\upsilon^{n+\frac{4}{3}}} \left(P_\upsilon(\mu) Q'_\upsilon(\mu_0) - Q_\upsilon(\mu) P'_\upsilon(\mu_0)\right) d\upsilon$$

(51)

where υ is a complex variable, P_υ and Q_υ are Legendre functions of the first and second kind and *C* is the contour defined in Figure 10. Again the straight line segments cancel so that the contour reduces to a circle, however, now the radius ρ is dependent on *R*.

The first step in the design of electrodes is the choice of beam type, beam current and final extraction energy. For each choice there is a different electrode design. It must

be determined from the first instance whether the beam is to be strip/wedge or cylindrical/conical and whether it is to be parallel, convergent or divergent. It must be kept in mind that the whole extractor is to act as if the beam was part of an entire diode from the plasma to the 0V equipotential. The electrode design is such that the extractor apertures follow the beam shape so that they are just in contact with the beam at their respective positions.

The Extraction Gaps

Stage 1

The extraction gap stage 1 comprises the aft face of the Plasma electrode and front face of the Accel electrode. Determining the beam distribution in this region, first takes into account that the electric field at the plasma/beam boundary is non-zero due to the plasma sheath, then given the beam form required the relevant solution can be arrived at by following the derivations above. This in turn is substituted into the relevant solution of Laplace's equation. Note that in this region the potential distribution is convex and that the electric field at the exit of this region is very large.

Stage 2

The extraction gap stage 2 comprises the aft face of the Accel electrode and the front face of the first Blocking electrode. The purpose of stage 2 is primarily to bring the electric field at the exit of stage 1 to zero. This is necessary as failure to do so will result in a strong ballooning of the electric field aft of the Accel aperture.

This will induce strong aberration and readjustment of the beam charge distribution leading to non-uniformity in the beam and potentially also reshaping of the meniscus away from the ideal plane, cylinder or sphere. The potential distribution in this region is obtained by solving Poisson's law backwards and assuming a non-negligible initial velocity. Again this expression is substituted into the relevant solution of Laplace's equation.

Laplace's equation, it seems, can not be solved (in the Real domain) for a boundary condition that changes convexity because this would require that the equipotentials overlap, which in terms of electrodes means that they would need to occupy the same space. In fact, this is only a major problem for the Accel electrode and a solution is to shape the electrode so that it is the median between the two ideal cases. It should be noted that close to the beam, the two equipotentials are almost identical and that away from the beam they are not strongly disparate.

Though the outer electrodes would eventually also overlap, and in practical terms would approach each other so that the inter-electrode gap would lead to break down, Radley has indicated that the effect of the electrodes away from the beam edge is increasingly negligible. Thus as a best approximation to an ideal extractor, the outer electrodes are made to extend to just outside break-down distance and the intermediate electrode is made to be the average of the two ideal equipotentials.

Blocking Electrodes

The Extraction electrodes have accelerated the beam just

beyond the desired extraction energy and have done so in such a way that the electric field at the exit of stage 2 is 0 Volts per meter. In the case were positive ions are being extracted, this means that the voltage at the exit of the Extraction region stage 2 is some negative value. The purpose of the Blocking electrodes is then to bring the beam potential back up to 0V whilst ensuring that the electric field upon exit is 0 Volts per meter. Assuming that this Blocking potential is sufficiently high this impedes the flow of electrons from aft of the extractor to the Extraction region.

Since the potential gradient is zero upon entry to the Blocking electrode stage 1, the standard Langmuir-Blodgett representation can be used for the beam potential. For stage 2, however, the presence of electrons can not be ignored since a population of higher energy electrons from the tail of the distribution will be able to penetrate some distance up the potential well. To solve for this distribution the relation given above is employed. This potential distribution is then substituted into the relevant solution of Laplace's equation.

Beam Neutralisation

Beam neutralisation is necessary aft of the extractor to compensate the considerable beam space charge. In many practical solutions, secondary electron emission from sputtering will be sufficient to provide a population of neutralising electrons. However, if this were not the case, some electron source would be required such as a hollow cathode. In this situation emphasis should be given to ensuring that the electrons are as low energy as possible to

avoid needing a large Blocking potential.

Plasma Density Range

There is a limit to how high the extraction energy can be taken as a function of density and beam form. For example at a plasma density of $10^{14}cm^{-3}$, no wedge beam form can be extracted without aberration because the minimum voltage per meter required for extraction is in excess of the breakdown limit of $10^{7}V/m$. At $10^{13}cm^{-3}$ extraction of all beam forms is possible, but for convergent beams the maximum extraction energy is capped at 20kV in the stage 1 of the extraction region. Above this energy, the electrodes need to be too close for breakdown.

Examples

Diverging Wedge Beam

For this example a 5° diverging beam is extracted through a 1mm wide, 1m long rectangular slit. The plasma source is assumed to be a Krypton plasma of density $10^{13}cm^{-3}$ at the sheath edge. The total extraction energy is 20kV and the total blocking potential 200V.

Extraction Gap Stage 1

The problem can be considered analogous to that of a complete cylindrical diode of curvature r_s=5.737mm. The current density flowing across the meniscus yields $B=7.6218\cdot10^{8}$ according to (12). The ratio of the sheath to the pre-sheath is given by first solving (6) for the boundary conditions set in (25):

$$\beta(\gamma_m) = \frac{15^{\frac{3}{4}}}{\sqrt{\frac{9}{2}Br_m}} = 1.71827\cdot10^{-3} \qquad (52)$$

and then solving (19) to find γ_m=1.71797·10^{-3}. From (7) R=1.00172 so that the sheath width is given by:

$$r_s 1.00172 - r_s = 9.9\mu m \qquad (53)$$

The gradient at the sheath edge in terms of γ_m is:

$$\frac{dV}{d\gamma}\left(\gamma_m = 1.71827\cdot10^{-3}\right) = 11644V/unit \qquad (54)$$

Since $\gamma = \ln\left(\frac{r}{r_s}\right)$, $d\gamma = \frac{dr}{r}$ which means:

$$\frac{dV}{dr}(r_m) \approx \frac{1}{5.737\cdot10^{-3}}\frac{dV}{d\gamma} = 2.03\cdot10^{6}V.m^{-1} \qquad (55)$$

According to (18), p=1.43557·10^{-2} which is well below the established limit of p_{limit}=0.15. In combining table 2 and equation (20) the series expansion of g is found to be:

$$1.05846\gamma - 0.521406\gamma^2 + 0.209569\gamma^3 - 0.0738154\gamma^4 + 0.0165584\gamma^5 - 0.00157496\gamma^6 \qquad (56)$$

and hence an expression for the voltage in terms of γ through relation (13). Using the multinomial theorem (56) can be rewritten to give the form:

$$1.0787 - 0.708501\gamma + 0.342937\gamma^2 - 0.140694\gamma^3 + 0.0419959\gamma^4 - 0.00842186\gamma^5 \qquad (57)$$

Since the wedge is divergent $\gamma = \ln(R)$, and we solve (44) with

$$\begin{cases} R = \sqrt{\tilde{x}^2 + \tilde{y}^2} \\ \theta = \tan^{-1}\left(\dfrac{\tilde{y}}{\tilde{x}}\right) \end{cases} \quad (58)$$

where the non-normalised coordinates are:

$$\begin{cases} x = r_m \tilde{x} \\ y = r_m \tilde{y} \end{cases} \quad (59)$$

For the aft face of the plasma electrode we solve (44) for V=0. To solve for the front face of the Accel electrode we solve for:

$$V = \frac{10.1kV}{\left(\frac{9}{2}Br_m\right)^{\frac{2}{3}}} = 0.138575 \quad (60)$$

which is a direct consequence of (41).

Extraction Gap Stage 2

At the entry to stage 2, V_{ext}=10.1kV. The solution to the g series is given by the standard Langmuir-Blodgett relation but derived backwards. Hence substitute:

$$g = \gamma + 0.4\gamma^2 + 0.0916667\gamma^3 + 0.01424242\gamma^4 + 0.001679275\gamma^5 + 0.0001612219\gamma^6 \quad (61)$$

into equation (44), but with $\gamma = -\ln\left(\frac{r}{r_d}\right)$ where r_d is the radius of the concentric surface at the exit of the stage. At this point in the calculation r_d is unknown, but by an iterative process a value can be found such that the potential gradient at r_a at the entry to the stage is equal to that of

the distribution at the exit of the previous stage. We define:

$$\gamma_a = -\ln\left(\frac{r_a}{r_d}\right) \qquad (62)$$

so that:

$$e^{-\gamma a} = \frac{r_a}{r_d} \qquad (63)$$

and:

$$r_d = r_a e^{\gamma a} \qquad (64)$$

Solve for γ_a so that:

$$\frac{dV}{d\gamma}\left(\gamma_a^-\right)\Big|_{stage_1} = \frac{dV}{d\gamma}\left(\gamma_a^+\right)\Big|_{stage_2} = 63586 \qquad (65)$$

noting that the g series in stage 1 is different to that in stage 2. Thus $\gamma_a = 0.35464$. The voltage at γ_a is V=.239885 according to (41).

The Decel 1 electrode front face is calculated by solving (44) for V=0 and the Accel aft face is calculated by solving (44) for V=.239885. It should be noted that the acceleration voltage in this gap is 17484V which is significantly higher than 101kV. To achieve a total acceleration energy of exactly 20kV, an iterative approach will be required. But since this does not benefit the illustration of the method, this will not be done here.

Because the particles have an initial energy of 10.1kV, the basic solution is shifted up by this amount.

Blocking Gap Stage 1

A blocking voltage of 200V is required so it is assumed that the voltage in this stage is 100V. The standard Langmuir-Blodgett relation is solved to determine the gap size. This yield $\gamma = .00712381$. Then to solve for this stage replace the standard Langmuir-Blodgett relation into (44). For the Decel 1 aft face V=0 is solved and for the decel 2 front face V=.00137203 is solved. The final solution is shifted up by 27584V.

Blocking Gap Stage 2

The solutions for the Poisson equation with the presence of Maxwellian electrons has not been resolved. For this reason this analysis does not assume the presence of electrons.

The gradient at the entry to the stage is 18729V/unit. Again the Langmuir-Blodgett relation considered backwards is used. The gap spacing that gives a gradient of 18729V/unit at the gap entry is $\gamma = .007196$. The normalised voltage at this point is V=0.00138794. To solve for the Decel 2 aft face (44) for V=0. To solve for the ground front face (44) is solved for V=0.00138794.

The electrodes defined in the previous sections assumed negative ions being extracted from 0 up to 27584V. The electrodes for the extraction of positive ions are identical except that the polarity of the field is reversed. Under

this scheme ions are extracted from 27584V down to 0V. The electrodes are schematically shown in Figure 5. An expanded view of the Blocking electrodes is shown in Figure 6.

DATED this 17th day of October, 2003.

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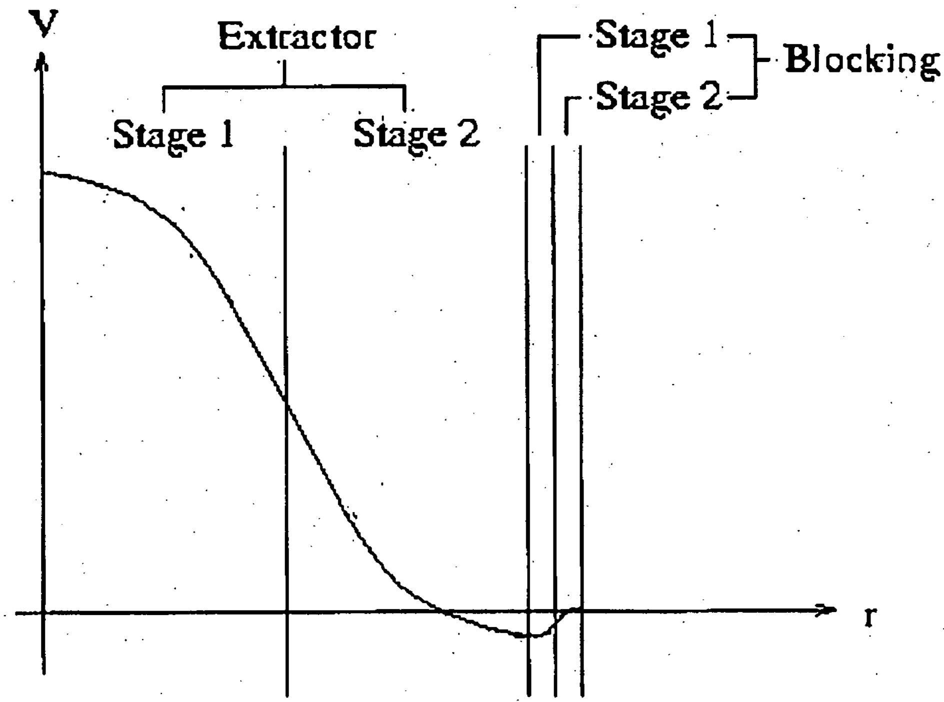

Figure 1

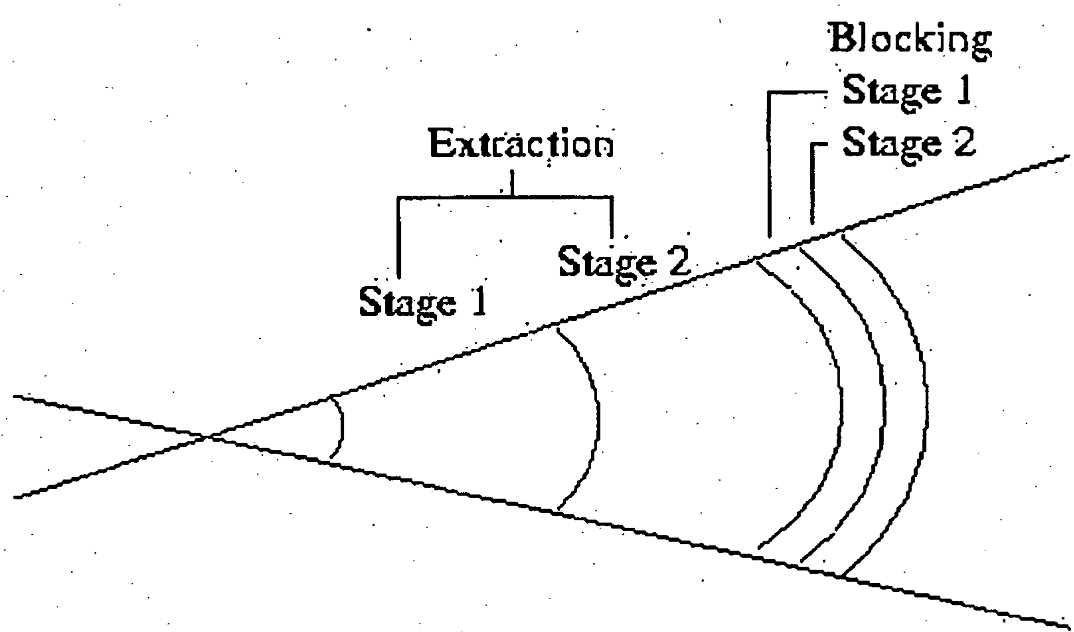

Figure 2

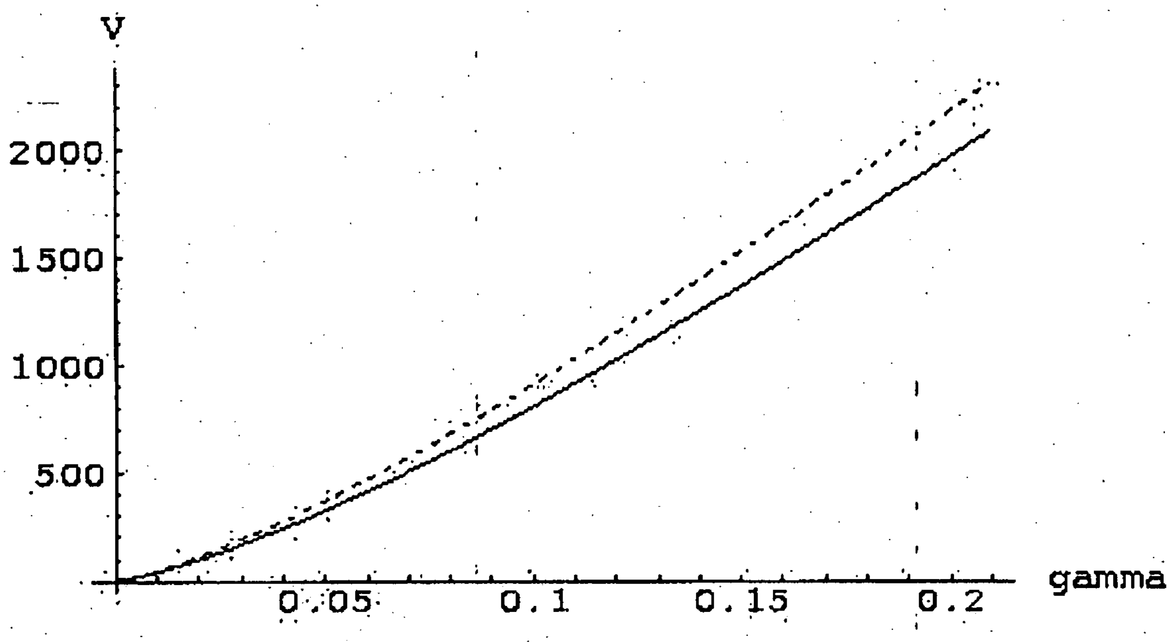

Figure 3

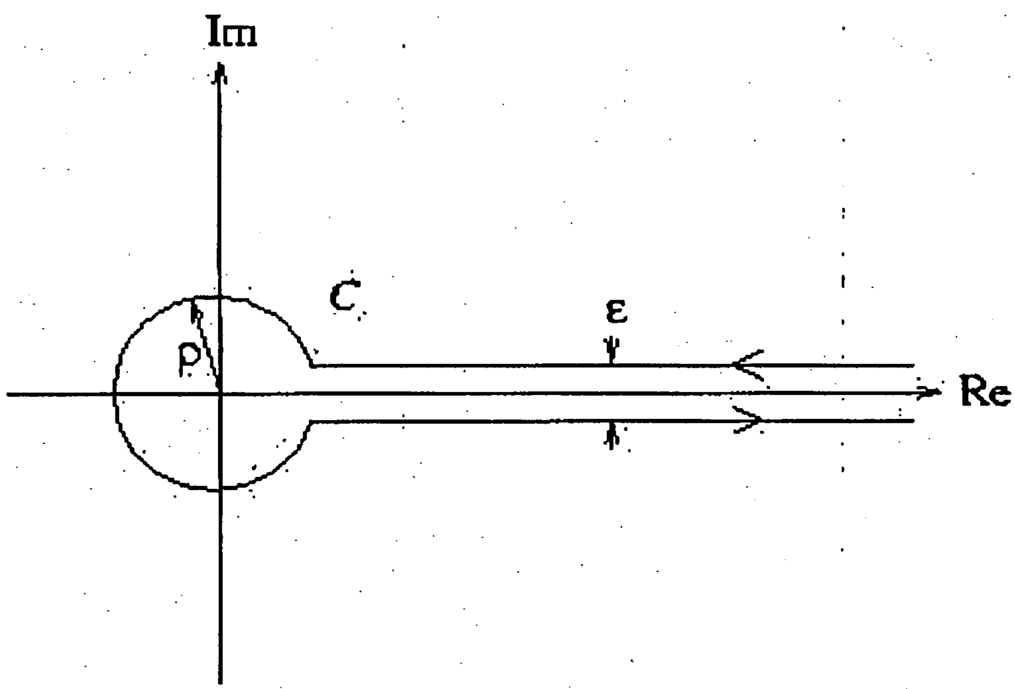

Figure 4

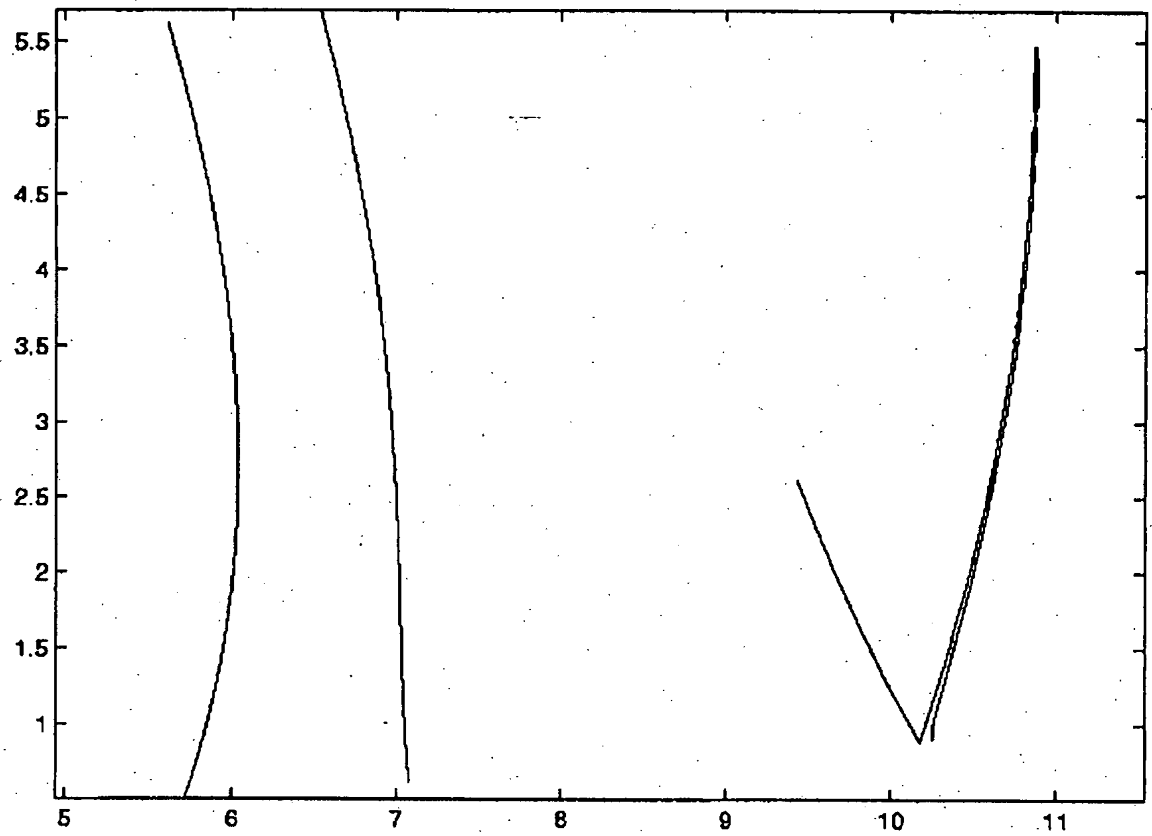

Figure 5

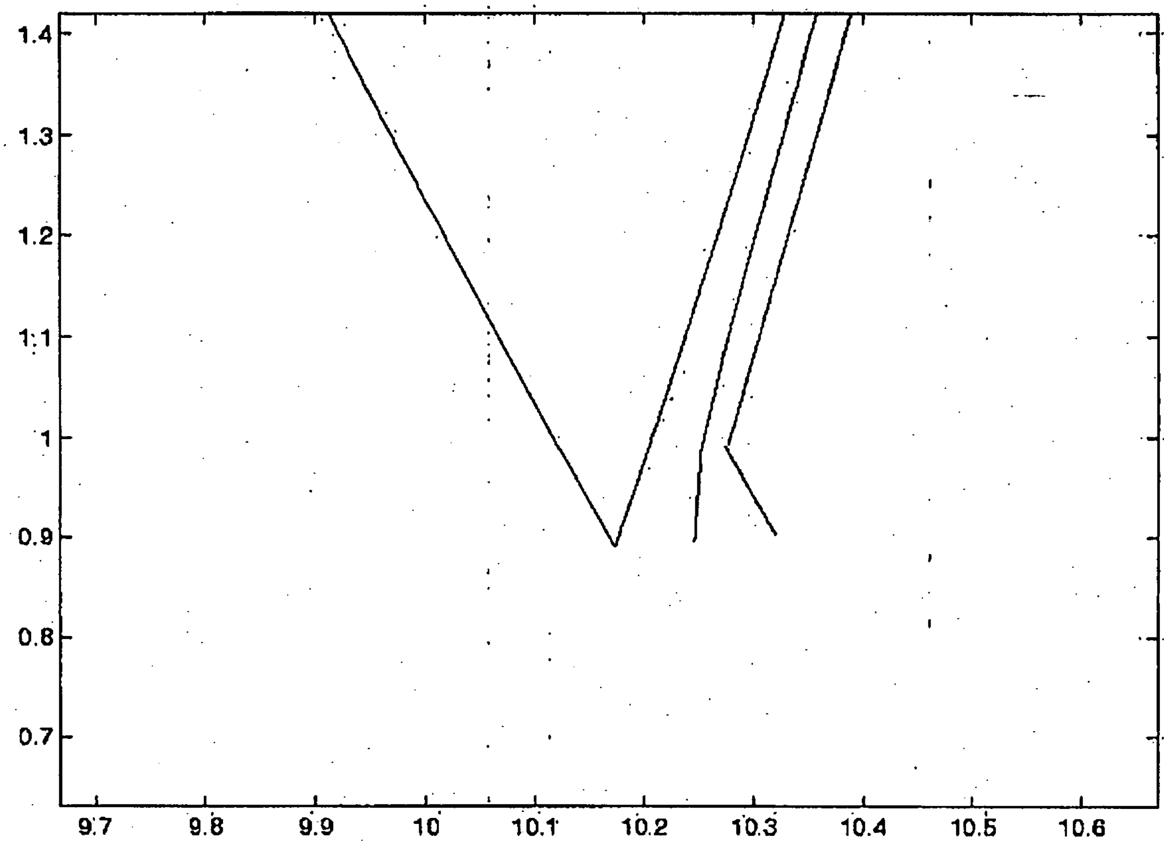

Figure 6